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SCHOOL OF ELECTRONICS AND COMPUTER SCIENCE

Network Coding for Cooperative Multi-user Wireless Communication Systems

by

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B.Eng, M.Eng

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Dedicated to my family
with all my heartfelt gratitute, appreciation and love...

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ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE
DEPARTMENT OF ELECTRONICS AND COMPUTER SCIENCE

Doctor of Philosophy

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In the first chapter, Space Time Trellis Codes (STTCs), Space Time Block Codes (STBCs) and Sphere-Packing-Space-Time Block Codes (SP-STBC) are reviewed. These schemes belong to the specific family of Multi-Input Multi-Output (MIMO) systems designed for achieving a diversity gain. The performance of the SP-STBC scheme is compared to other coded conventional modulation systems, namely to that of STBC-Phase Shift Keying or Quadrature Amplitude Modulation (STBC-PSK/QAM) and to that of STTC-Phase Shift Keying or Quadrature Amplitude Modulation (STTC-PSK/QAM). The rest of this chapter reviews other preliminaries pertaining to the context of cooperative communications and network coding.

In Chapter 2, an in-depth study of the capacity and outage probability of the Continuous-input Continuous-output Memoryless Channel (CCMC), Discrete-input Continuous-output Memoryless Channel (DCMC) and of Differential Discrete-input Continuous-output Memoryless Channel (D-DCMC) is presented. The study also considers various propagation phenomena, namely the small-scale fading and the large-scale fading. The frame-length is also taken into consideration when calculating the achievable throughput and outage probability, which serve as useful benchmarks for our near-capacity coding schemes. Extrinsic Information Transfer (EXIT) charts are used for designing Irregular Convolutional Coded Unity Rate Coded M-ary Phase Shift Keying (IrCC-URC-MPSK), Irregular Convolutional Coded Unity Rate Coded Differential M-ary Shift Keying (IrCC-URC-DMPSK) and Irregular Convolutional Coded Unity Rate Coded Space Time Trellis Coded M-ary Phase Shift Keying (IrCC-URC-STTC-MPSK) schemes.

In Chapter 3, a novel Distributed Concatenated IrCC-URC-STTC (DC-IrCC-URC-STTC) scheme is proposed for cooperative single-user systems relying on single-antenna aided relays, based on the studies conducted in Chapter 1 and Chapter 2. In this contribution, each coding arrangement of the entire DC-IrCC-URC-STTC scheme is designed for achieving decoding convergence to a vanishingly low Bit Error Ratio (BER) by employing non-binary EXIT-charts. Additionally, the EXIT charts are employed for calculating the most appropriate positions of the relays by ensuring that decoding convergence to a vanishingly low BER occurs at a similar Signal-to-Noise Ratio (SNR) both at the relays and at the destination.

In Chapter 4, Multi-User Cooperative Communications is designed for supporting M users

with the aid of near-capacity network coding. We first derive the upper and lower Frame Error Ratio (FER) performance bounds of cooperative multi-user communications systems using network coding. Then, we investigate Near-Capacity Multi-user Network-coding (NCMN) based systems using the IrCC-URC-MPSK scheme of Chapter 2. In parallel to the investigation of coherent NCMN systems, we also explored Near-capacity Non-coherent Cooperative Network-coding aided Multi-user (NNCNM) based systems using the IrCC-URC-DMPSK, which do not require channel estimation at the receiver's side. This reduces the complexity imposed, albeit this is achieved at a 3 dB SNR-loss. Moreover, a new technique referred to as the Pragmatic Algebraic Linear Equation Method (PALEM) was proposed for exactly determining the number of information sources that may be recovered from the composite NCMN stream, which results in a more accurate evaluation of the attainable FER performance of the NCMN and NNCNM based systems. The design principles presented in this contribution can be extended to a vast range of NCMN and NNCNM based systems using arbitrary channel coding schemes.

In Chapter 5, the NCMN and NNCNM based systems of Chapter 4 are generalised for introducing the Generalised NCMN (GNCMN) system, which has a multi-layer architecture and it is capable of operating in multiple modes. More specifically, the GNCMN system may operate upon employing either individually or in a combined fashion using a single Channel Coding (CC) layer plus two network coding layers, namely Network Coding 1 (NC1) and Network Coding 2 (NC2). Additionally, the GNCMN system is capable of simultaneously exploiting the advantages of all the modes available in each layer of the system as well as appropriately combining the advantageous modes across all the three layers.

Finally, in Chapter 6, the summary of our findings are presented in order to facilitate our discussions on future research.

Declaration of Authorship

I, **Hung Viet Nguyen**, declare that the thesis entitled

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and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published.

Signed: ..... Date: .....

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List of Publications

Journals:

1. **Hung Viet Nguyen**, Soon Xin Ng, Lajos Hanzo, "Performance Bounds of Network Coding Aided Cooperative Multiuser Systems," IEEE Signal Processing Letters, Vol.18, No.7, pp.435-438, July 2011.

2. **Hung Viet Nguyen**, Xu Chao, Soon Xin Ng, Lajos Hanzo , "Non-coherent Near-capacity Network Coding for Cooperative Multi-User Communications," IEEE Transaction on Communications, vol.60, issue 10, pp.3059-3070, Oct. 2012.

3. **Hung Viet Nguyen**, Soon Xin Ng, Lajos Hanzo , "Irregular Convolution and Unity-Rate Coded Network-Coding for Cooperative Multi-User Communications," IEEE Transaction on Wireless Communications, vol.12, issue 03, pp.1231-1243, Mar. 2013.

4. Jing Zuo, Chen Dong, **Hung Viet Nguyen**, Soon Xin Ng, Lie-Liang Yang and Lajos Hanzo, "Cross-Layer Aided Energy-Efficient Opportunistic Routing in Ad Hoc Networks," *submitted to IEEE Transaction on Communications, Oct. 2012*.

Conferences:

1. **Hung Viet Nguyen**, Soon Xin Ng, Lajos Hanzo , "Distributed Three-Stage Concatenated Irregular Convolutional, Unity-Rate and Space-Time Trellis Coding for Single-Antenna Aided Cooperative Communications," IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall), Ottawa, Canada, pp.1-5, 6-9 September 2010.

2. Jing Zuo, **Hung Viet Nguyen**, Soon Xin Ng, Lajos Hanzo , "Energy-efficient relay aided ad hoc networks using iteratively detected irregular convolutional coded, unity-rate coded and Space-Time Trellis Coded transceivers," IEEE Wireless Communications and Networking Conference (WCNC), Cancun, Mexico, pp.1179-1184, 28-31 March 2011.

3. **Hung Viet Nguyen**, Soon Xin Ng, Luiz Rebelatto, Yonghui Li and Lajos Hanzo, "Near-Capacity Network Coding for Cooperative Multi-User Communications, " IEEE 74th Vehicular Technology Conference Fall (VTC 2011-Fall), San Francisco, USA, pp.1-5, 5-8 September 2011.

4. **Hung Viet Nguyen**, Xu Chao, Soon Xin Ng, Luiz Rebelatto, Yonghui Li and Lajos Hanzo, "Near-Capacity Non-Coherent Network-Coding Aided Scheme for Cooperative Multi-user Communications, " IEEE 74th Vehicular Technology Conference Fall (VTC 2011-Fall), San Francisco, USA, pp.1-5, 5-8 September 2011.

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